Shape-Change for Zoomable TUIs: Opportunities and Limits of a Resizable Slider

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Abstract. Tangible sliders are successfully used as they do not need visual attention. However, users need to balance between opposite concerns: size and precision of the slider. We propose a resizable tangible slider to balance between these concerns. Users can resize the on-screen representation of the slider by resizing the tangible slider. Our aim is to benefit from both tangibility and flexible control, and balance between precision and minimum size. We measured the pointing performance of our prototype. We also assess the potential drawback (additional articulatory task for deformation) by evaluating the impact on precision of the additional articulatory task for deformation: for pursuing a target, we show that our resizable prototype supports better precision than its small counterpart as long as users do not need to resize it more often than around every 9 seconds.

Keywords. Resizable Interfaces, Zoomable Interfaces, Shape-Changing Interfaces, Tangible Interaction, Distant Interaction.

1 Introduction

Tangible User Interfaces (TUIs) benefit users when the visual attention is not on the input interface but on a distant target thanks to their tangibility [10][15]. As a consequence, TUIs have been extensively used. Example applications include lighting design with mixing tables and data visualization and manipulation on wall-sized displays [15].

When interacting with a distant target, users sometimes need to balance between opposite requirements: minimum size vs. precise manipulation of the TUI. Existing fixed-shaped TUIs are limited to a fixed and single compromise between these opposite requirements. For instance, mixing tables are very large and prevent their users from mixing at different location and e.g., get a different viewpoint on the scene. To overcome this limitation, we explore resizable TUIs. In particular, as tangible sliders are widespread, we focus on them for exploring the opportunities and limits of resizing for zoomable TUIs. For instance, to browse an on-screen timeline, a small tangible slider allows coarse browsing of the whole period, a medium tangible slider allows to browse days, and a long tangible slider allows to precisely browse minutes.

An alternative solution would be to provide users with multiple sliders of different sizes. Sliders in the industry come in a large range of sizes. For instance, few millimeters long slider switches for mobile devices to 10cm long sliders on mixing consoles. However, when size is critical, for instance when walking or craving for space on a table, multiplying the number of sliders is not an optimal solution. On the contrary, a resizable slider can give the user the opportunity to compromise on the precision in order to lessen the size.

In this paper we investigate the concept of resizable tangible sliders. We allow zooming up in motor and visual space when precision is critical, and zooming down when space is restricted. Users can enlarge the slider to get more definition and be more precise. Users can also shrink the slider to gain space and still interact, e.g. while seating at an encumbered desk. Doing so, users can benefit from both the physicality of tangible sliders and malleable control of digital sliders. We build proof-of-concept prototypes of such a resizable slider and integrated them in two example applications among our three envisioned scenarios of use. Beyond proposing a new tangible interaction technique, we measure its pointing performance and relate it to a second experiment assessing its possible flaw: the additional articulatory task and time needed for resizing. We show that the drawback of the resizable slider does not compromise its benefit: in our experiment, if the user does not need to resize more often than around every 9 seconds, our resizable tangible slider allows better precision compared to a small fixed-shaped tangible slider. In addition, the studies allowed us to identify how our particular proof-of-concept prototype can be improved for increasing the performance of such a novel tangible interaction technique.

After reviewing how previous research contributed to this work, we present our prototype and its applications. We then report user experiments evaluating its benefits and limitations, before concluding.

2 Related Work

We build upon the extensive related work in the area of multiscale interaction, shape-changing tangible user interfaces and interaction with sliders. We review the sub-area of work in these spaces that contributed to resizable tangible sliders for zoomable TUIs.

Interaction at Multiple Scales. The relationship between scale and performance has been studied for different tasks. All studies [1][3][12][18] converge toward showing that the larger the scale, the better the performance. Recent work [7] demonstrated the importance of both motor and visual scale for the selection of small targets with a mouse [7]. We build on this work for the design of our zoomable tangible slider.

We found several techniques leveraging the idea of visual scale for improving performance, in particular within Graphical User Interfaces (GUIs). *Pad++* is a zoomable interface that allows navigation in a multiscale application [4]. The mouse's left button controls the cursor, the middle button zooms in and the right button zooms out. *Pointing lenses* [20] proposed to enlarged onscreen targets for selecting them with a pen on a tablet. *TapTap* [22] allows zooming on the area of a small target with a first tap with the thumb on a small touch-screen, and then select the enlarged target with a second tap. *Speed*, *Key* and *Ring* [2] introduced the coupling of motor and visual aspect in zoomable GUIs. However, these GUI techniques lack the benefit of tangibility. No zoomable tangible slider has been proposed yet, as it is not straightforward to design a shape-changing slider to be scaled in motor space.

Shape-changing Tangible User Interfaces. Future challenges of Shape-Changing Interfaces have been explored [21]. However, the idea of shape-change to compromise between size and precision was not proposed. Shape-changing interfaces characterized in [23] aim at actuating the shape in order to change the grip and affordance. We extend this characterization by relating shape-change to control properties (scale and definition), and let the user initiate the change of shape. Resizable displays have been proposed through folding/rolling/coupling displays [16][17][19][25][24]. The authors explored resizing in two ways: first, to increase the display real estate; second, as an input technique itself. They do not leverage the change of shape for modifying control properties. Also, the widgets projected on these resizable surfaces lack the tangibility that was proven efficient in previous work [10][15].

The change of control through the change of shape has been proposed in three previous works. First, stiffness-changing of the control has been explored [11]. However, this impact of the stiffness on the performance has not been evaluated yet. Second, with a different technology, *ForceForm* allows users to sculpt an interactive surface to create tangible controls [29]. Although promising, this technique requires users to carry a large surface and does not address the problem of size. Third, *TransformTable* [27] is a self-actuated shape-changing digital table with three predefined shapes: round, square and rectangle. It allows accommodating single and collaborative use of an interactive surface. This approach does not address tangibility and user-controlled continuous resizing.

Interaction with tangible sliders. Tangible sliders on the keyboard's side have been studied for interacting with scrollbars of GUIs [8]. We extend the knowledge on interaction with sliders by studying its resizable properties for zooming.

The performance of tangible sliders has been compared to digital sliders. A study [28] showed no significant difference in performance between tangible and untangible slider when the corresponding display is superimposed. However their tangible slider suffers from implementation problems. On the contrary, other comparative studies between digital and tangible sliders [15][26] showed that tangible sliders help users focus on the distant targets. We build on this work by considering interaction with distant targets.

Zebra Sliders [6] allow the superposition of tangible sliders on a primary capacitive surface. Using this approach, a second fixed slider on top of another can alter its control properties. Although the performance can be improved, the multiplication of the number of sliders increases the size.

To conclude on previous research, the large body of work on multiscale interaction in the GUI paradigm showed that zoomable interfaces have a great potential for easing the selection of very small targets. However, none of this knowledge has been transferred to TUI. Shape-changing interfaces very recently started to explore the opportunities of shape-change. However, the potential for zoomable interfaces has not been explored yet. Finally, interaction with tangible sliders has been proven efficient when the target is distant. However, the balance between efficiency and size has not been addressed. We now present the design, prototype and applications of a resizable slider that aim at balancing size and performance in selecting distant targets.

3 Design, Prototype and Applications

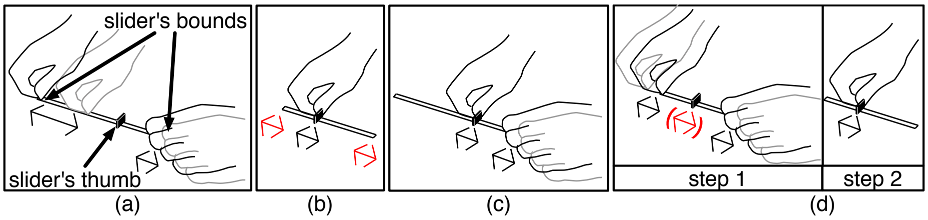

Fig. 1. Design alternatives for our resizable slider and the one we study in this paper (d). (Black/red) arrows show elements that can be moved (by the user/system).

Design. Fig. 1 shows the design alternatives that we considered. In (a), the slider's thumb is fixed and the user simultaneously resizes to zoom and moves the slider's bounds to point. A drawback is that the space necessary to interact is large. In (b), the user only manipulates the thumb and the slider is resized by the system. A drawback is that it only suits a target-aware system. In (c), one bound is fixed and the user simultaneously zooms with the other bound and points with the slider's thumb. A drawback is that the user cannot freely place the slider. **Fig. 1**(d) shows the design that we study in this paper: zooming is performed with two hands, one on each bound of the slider. We chose to study the efficiency of this design first, as it did not have the drawbacks of the others. Future work can compare the alternatives to find which offers the best compromise between performance, footprint and mobility.

Prototype. Before addressing the technological issues for making such resizable sliders, we aim at studying the relevance of the concept. As resistive, capacitive, optical or magnetic embedded technologies currently used for tangible sliders are difficult to adapt for physically extension, we used external tracking to prototype a high-resolution proof-of-concept resizable tangible slider (**Fig. 2**). We used a retractable and rigid measuring tape as a smooth slide rail for the slider's thumb. For the bounds, we laser-cut two boxes. One of them hides the body of the measuring tape. The button to retract the measuring tape was made accessible to the user through a hole in the corresponding box. For resizing the slider, the user brings the bounds closer/further while pressing the button. For the slider's thumb, we laser-cut a piece to slide on the measuring tape. For better yaw stability, we (1) made the thumb 9 mm large and (2) made it to measure so that it perfectly fits the tape's shape and dimension. For better pitch stability, we added buttresses to the slider's thumb so that it stays horizontal when it slides. Buttresses were positioned far enough from the tape in order for them not to prevent the slider's thumb to reach the bounds. This physical prototype ensures that the tangible interaction takes place smoothly and efficiently as expected by the users.

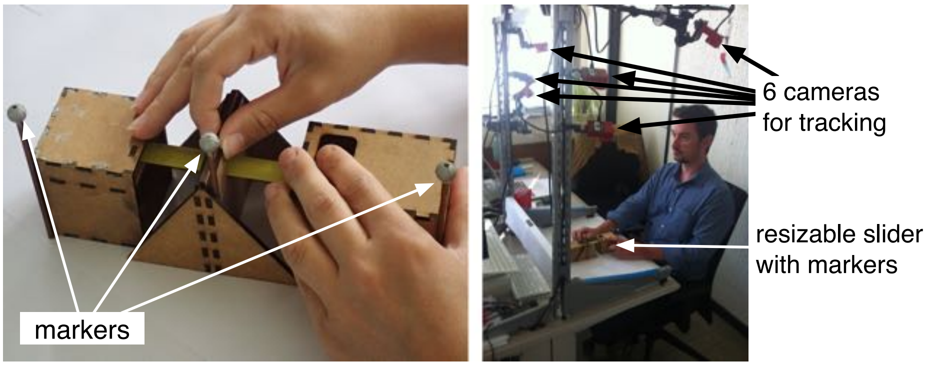

Fig. 2. (Left) Prototype of a resizable tangible slider. A rigid retractable measuring tape allows for the laser-cut thumb to slide on the slider's range. Three reflective markers are tracked by an infra-red tracking system with 6 cameras (right), detecting relative positions of the reflective markers placed on the bounds and the thumb (left).

We track the position of the upper and lower bounds and of the thumb through three reflective infra-red markers and six cameras (OptiTrack Flex V100R2 infrared cameras from NaturalPoint). The tracking system is placed on a table to allow users to comfortably manipulate the slider with their elbows resting on the table. Cameras were placed as close as possible to the slider in order to maximize its resolution. Indeed, the resolution is a variable of the cameras, their number and their position. We measured the resolution of the slider as in [5] by four standard deviation of the sensed position of the static device. Throughout 500 measurements of the position of the static thumb (in fixed bounds), we found a resolution of 0.009 mm, i.e. 2822 dpi. The resolution was constant over all sizes of the slider. High-resolution mice are about 2000 dpi. As a consequence, we do not expect the resolution to limit the interaction, even in the smallest sizes like 2cm long slider for instance.

Example applications. Sliders are “a standard way to adjust continuously varying parameters” [26]. For most existing applications, users’ needs for space and precision vary between uses or while using them. We illustrate the applicability of our approach through three example of these applications: our envision of future mixing consoles and two of our implementations (visualization and graphics edition).

Mixing consoles are widely used for sound, light or video in a variety of domains like public address systems, recording, film, broadcasting and television. First, users currently make a fixed performance/size compromise before use by selecting a particular console beforehand. Mixing consoles come in a wide range of sizes, with 20/30/45/60/100mm sliders, depending on the size of the whole console. Our resizable sliders can be brought together to make a resizable console and help them make the best of each particular situation with one single console.

Second, users currently also change compromise during use: e.g., when engineers need to adjust mixes from the performers' positions on stage or from the front/back/edge rows of the venue, current solutions include verbal directions from a second engineer or non-tangible, less efficient [15] remote control of the console via a tablet[1]. Bringing the subset of necessary sliders to the particular location and resizing them to fit any support surface found on site would help improve performance during high-pressure (pre-)show setup. This would be an opportunity to keep the eyes-free ability to control multiples values simultaneously, make the best compromise between space and performance, and save time and human resources.

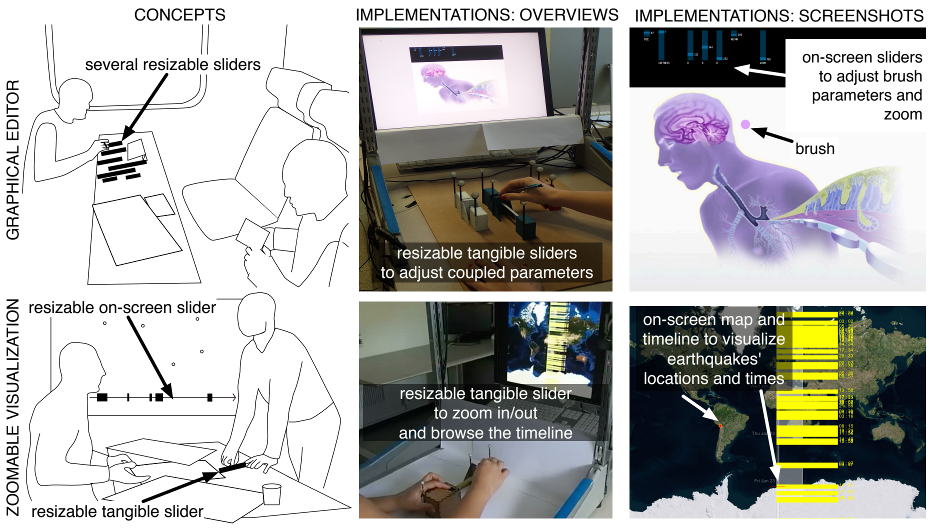

Fig. 3. Concepts (left) and implementations (center and right) of two applications of resizable sliders (black in concepts): (top) an illustrator works with sliders in a train to adjust brush parameters and (bottom) seismologists work around a table and zoom a timeline of earthquakes. The zoomable sliders are used to adjust to the available space and to the precision requirements.

Zoomable visualization currently rarely uses tangible sliders, but rather graphical sliders. However, previous work showed that visualization would benefit from tangible interaction [9][15]. We build on this previous work and argue that it would further benefit from *zoomable* tangible interaction, as users need to explore data at different scales. In particular, some targets can be very small and their relative size cannot be changed as it conveys information.

To illustrate this (**Fig. 3**, bottom), we developed an application for seismologists to visualize past week's earthquakes on the world map. The application shows an earth map in full screen and a superimposed timeline, representing respectively place and

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[1] https://synthe-fx.com/products/luminair, last retrieved April 30th 2015.

time of earthquakes that occurred in the previous week. The prototype is mapped to the timeline. The slider's size allows for continuous zooming of the timeline. The slider's thumb allows selecting earthquake(s) on the timeline. In this continuous time dimension, both events and empty spaces convey relevant information to seismologists, through patterns or density, to gain insight and predict the future.
In our scenario, when Louis works with his team around a table in front of a wall-mounted screen, he can explore the earthquakes with the tangible slider on the table. He scales it up when in need to precisely select a single earthquake and scales it down when precision is less important than examining the documents lying on the table.

Graphical editors' interface includes a large number of graphical sliders for adjusting parameters, e.g., brush's size, softness, color. They are currently rarely used with tangible sliders. However, previous work showed that it would benefit from tangible interaction to more efficiently switch between parameters [10]. We build on this previous work and argue that it would further benefit from resizable tangible interaction: on the one hand, sometimes users' priority is not to be precise but they rather quickly draft many ideas, quickly switching between parameters. On the other hand, sometimes users' priority is to precisely adjust parameters to achieve high quality.
To illustrate this (**Fig. 3**, top), we developed a simple graphics editor that couples several resizable tangible sliders with corresponding zoomable graphical sliders among the most used: the zoom, and the brush's size, softness and color.
In our scenario, Helen works as a freelance medical illustrator. She meets with clients at their workplace, and never knows in advance the space available. She brings her tablet and her sliders as she can reduce them to minimum size for transport. When on site, she can use as many and as large sliders as possible to quickly switch between parameters and quickly draft ideas with the clients. On her way home, she often works on the train. Until the first stop, the train is almost empty so she takes advantage of the space and enlarges the sliders as much as possible for better performance. Then, a passenger sits next to her and she politely shrinks the sliders to share the table. Continuous resizing is here a high benefit. In general, continuously resizable sliders are promising for adapting to ad-hoc interaction around a table: depending on the space available on the table and the task precision, users can reach the best compromise at any time through resizing. In the future, continuously resizable sliders can be coupled with resizable displays [17][19][25].

4 Pointing performance of the prototype

From [7], it is clear that larger sliders should perform better. However, it is not clear *how much* better our prototype is when larger, as [7] used a mouse. As we evaluate later in the paper the drawback of our system, it is important to compare its drawbacks to its benefits. Therefore, we conducted a preliminary experiment to measure the pointing performance of this slider at different scales.
Participants and Apparatus. Twelve right-handed participants took part in the study (6 female), aged from 21 to 42 years old (M=30, SD=6). The users seated 70cm away

from a 1600×1200px (41.2×30.8cm) display. The thumb of the prototyped slider (see section 3) was manipulated on a table. The slider was prepared with a fixed size before each block and could not be resized during the block.

Experimental Design. We used a within subject design, with task's **Scale** and task's level of difficulty (**ID)** as independent variables.

We had three levels of Scale. The smallest scale, involving manipulation of the thumb with fingers only, consisted in a 2cm long tangible slider and a 96px long slider on the display. The medium scale was twice the smallest scale (4cm/192px) and involved manipulation with fingers and wrist. The largest scale was twice the medium scale (8cm/384px) and involved manipulation with fingers, wrist and elbow. The cursor size was 1px large for all scales.

We had four levels of difficulty: Fitts' indexes of difficulty (ID) close to 2 (very easy), 3, 4 and 5 (very difficult): 2.00 and 2.12 were very easy, 2.81 and 3.09 were easy, 4.00 was difficult and 4.95 was very difficult. We used 2 distances between the starting position and the target (D) and, for each D, 4 corresponding target widths (W), given by ID=log2(D/W+1). For the smallest scale (2cm/96px), D={30,60}px and W={1,2,4,10} and {2,4,9,20}px respectively. For each D, the higher the ID is, the smaller the target's width is. For medium scale D and W were twice the value of the smallest scale and for the largest scale, D and W were twice the value of the medium scale.

Task and Procedure. Subjects were asked to be as fast and accurate as possible. Each block started with training, as long as the subject needed. Then, the trial started as soon as the subject pressed a key with their left hand on a keyboard below the display. A thin vertical white slider was displayed on the screen (**Fig. 4**). Users had to move the slider's thumb so that the white user's cursor coincides in the green target cursor. The error is shown in red between user's and target cursor. Like a typical computer pointing task, the task had to end successfully. Thus the error rate was forced to zero as in [7]. When the task finishes, as soon as they correctly validated by pressing a key, the next target appeared at a predefined distance from the previous target.

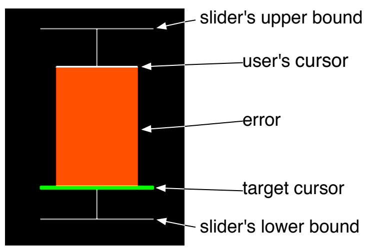

Fig. 4. Close-up screenshot of the experimental pointing task with the 8cm/384px slider.

A pseudo-random series of 80 trials (10 times each possible task) was build. This series was split into 2 blocks of 40 trials to allow a pause in the middle of the series. The two blocks were repeated for each Scale, making each participant perform 80×3=240 trials. The three scales were counterbalanced across the 12 participants through a Latin square. We collected 2880 trials, through 12 participants × 10 repetitions of each task × 3 scales × 4 widths × 2 distances.

Results. We considered the movement time (**MT**) and **error rate** as dependent variables. Error rate was computed as the number of times a validation occurred while the cursor was not within the target. **Fig. 5**[2] shows the impact of ID and scale on the mean movement time (MT) and error rate.

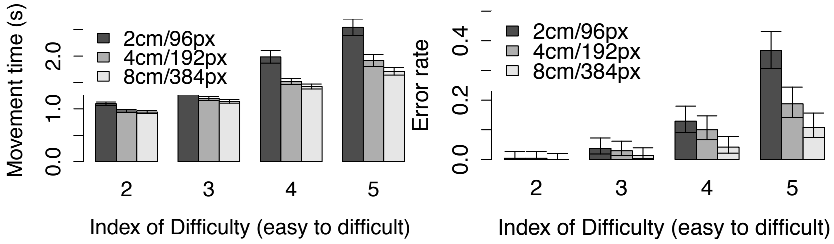

Fig. 5. Impact of task's ID and scale on the mean movement time (left) and error rate (right).

Movement time. A Levene's test revealed that we could not assume the homogeneity of variances. As a consequence, we performed our analysis through a Friedman non-parametric test. The test revealed an impact on MT for ID ($\chi2$=1496, p<.001) and scale ($\chi2$=464, p<.001). Post-hoc tests using Wilcoxon test with Bonferroni correction showed significant differences between all four IDs (p<.001) and between all scales (p<.01 between medium and large scales; p<.001 for all other scales). As shown in **Fig. 5**, for a very easy task (ID=2), small and medium scales are significantly (p<.001), but little different: medium scale takes 0.87×MT of small scale (i.e. 0.14s gain). And medium and large scale are not significantly different. **For a very easy task, the slider's size has no to little impact.**

For ID=3, large scale takes 0.95×MT of medium scale (i.e. 0.06s gain) (p<.01), itself taking 0.81×MT of small scale (i.e. 0.30s gain) (p<.001). For ID=4, large scale takes 0.94×MT of medium scale (p<.01) (i.e. 0.10s gain), itself taking 0.74×MT of small scale (p<.001) (i.e. 0.56s gain). For ID=5, large scale takes 0.87×MT of medium scale (p<.001) (i.e. 0.27s gain), itself taking 0.75×MT of small scale (p<.001) (i.e. 0.70s gain). **For these higher difficulties, the larger the slider, the bigger the size but the better the performance. It is then up to the user to compromise on one or the other.** We measured the strongest effect for the user for very difficult targets (ID=5), where the large scale takes 0.65×MT of the small scale (i.e. 0.98s gain), for a device 1.75 larger (i.e. 6cm). **The gain in size and performance are different, but their respective importance is up to the user.**

Error rate. Pearson chi's square test for proportions shows an impact on the error rate of ID ($\chi2$=265, p<.001) and scale ($\chi2$=55, p<.001). More particularly, as shown in **Fig. 5** (right), large scale leads to 0.42 times the errors of medium scale for ID=4 ($\chi2$=5, p<.05) (i.e. error rate 6% lower). For ID=5, large scale leads to 0.58 times the errors of medium scale ($\chi2$=5, p<.05) (i.e. error rate 8% lower), itself leading to 0.51

[2] In all figures, error bars show 95% confidence intervals.

times the errors of small scale ($\chi 2=18$, $p<.001$) (i.e. error rate 18% lower). **We measured the best benefit for the user in error rate for difficult targets (ID=5) where the large scale leads to a third of the errors of the small scale** (i.e. error rate 26% lower) **for a device 1.75 larger** (i.e. 6cm).

Discussion. Through this experiment, we measured the balance our prototype offers between size and pointing performance. For performance particularly, this experiment is not a strict, but a "conceptual" [14] replication of previous work [7]: it aimed at measuring earlier findings in different settings. Previous work [7] showed that motor and visual magnification at constant resolution (*Zoom* [7]) helps the acquisition of very small targets of a GUI with a mouse. In our experiment, we investigate the results of the same scaling method using a different device. D (2,4,8,16px [7]) and W (1,2,4,8px [7]) combinations are also different, as we wanted to allow for more representative range of manipulations of the slider and evaluate the slider with a wider range of targets' widths, even though including small targets (e.g., 1,2,4px). In addition, they explored the scales of 1, 4, 16 and 64, but we preferred to focus on scales that are more likely to physically occur with TUIs: 1, 2 and 4. Keeping in mind these experimental differences and similarities, we compare[3] the results between scales 1 and 4: for MT, they (we) found that scale 4 leads to 1.33 (1.29) times faster selection than scale 1. For the error rate, they (we) found that scale 4 leads to 46% (70%) less errors than scale 1 with Zoom. Although the results for MT are comparable, the difference in error rate is more important in our experiment. As the resolution of our prototype was high (as in [7]), we hypothesize that the static friction of our prototype is responsible for this difference: we felt that very small corrections performed with the thumb of our prototype were slightly more difficult than with a mouse. Future improvement of the prototype will investigate ways of decreasing the force needed to start moving the thumb.

Another comparison with previous work can be done through standard Fitts' analysis [7]: ours lead to $MT=0.50+0.31\times ID$ (adjusted $R2=0.98$) for the small scale, $MT=0.44+0.25\times ID$ (adjusted $R2=0.99$) for the medium scale and $MT=0.46+0.23\times ID$ (adjusted $R2=0.99$) for the large scale. 95% confidence intervals show that these regression lines only differ significantly between the small scale on the one hand and the medium/large scales on the other hand (for ID>2). This is consistent with previous findings [7] (Section 5.3): they found the small scale to decreased their fit to a Fitts' model common to all scales.

We now present the evaluation of a main limitation of our resizable slider.

5 Impact of Resizing on Performance

The aim of the experiment is to answer the following question: how is the additional resizing task affecting the performance of the resizable slider compared to small and large sliders?

[3] We did not compare the effect sizes, as there is no straight way to compute the effect size of the non-parametric Friedman test that we had to use.

Participants and Apparatus. Nine right-handed participants took part in the study (5 female), aged from 21 to 49 years old (M=31, SD=8). The participants seated 70cm away in front of a 1600×1200px (41.2×30.8cm) display. The prototyped slider (see section 3) was manipulated on a table. The same resizable slider was either prepared with a fixed size before each block and could not be resized during the block; or resized by the user during the block.

Experimental Design. We used a within subjects design with the following independent variables:

- Three **Sliders**: Large (8cm) fixed-size tangible slider (L), Resizable tangible slider (R), and Small (2cm) fixed-size tangible slider (S).
- Four **Intervals** of difficulty change: every 3/9/18/30 seconds, the difficulty randomly changed between 3 levels of difficulty. The three levels of difficulty were 1, 2 and 4px of target's widths when the slider was small (2cm). When the slider was large (8cm) then the three corresponding target's widths were 4, 8 and 16px. In the case of the resizable slider, the user was asked to resize the slider when the difficulty changed so that the target's width reached 4px.

The order of the Sliders was counterbalanced across the 9 participants through a Latin square and the four Intervals were randomized for each technique. We collected 5 hours and 24 minutes of trials in 216 trials of 90 seconds (9 participants × 2 repetitions of each trial × 90 seconds long trial × 3 techniques × 4 intervals of difficulty change). From the collected data, we removed the first 3 seconds of each trial as participants had to first catch up with the continuous pursuit task. The experiment lasted 36 minutes (+ training) for each participant.

Task and Procedure. Participants were asked to follow a target cursor as in previous work with sliders [10][15], as many higher-level tasks depend on it [15] like smooth adjustments of parameters in time. In **Fig. 6**, this task in presented on the right hand-side of the screen. Participants controlled the white cursor to follow the blue, moving cursor (target), i.e. to move the slider's thumb so that the white cursor coincides in the blue target cursor at all times. This allowed us to evaluate the impact of the additional articulatory task for resizing on this *continuous* pursuit task. The cost of resizing was then measured as the impact of the primary, resizing task on the performance of this secondary, pursuit task.

The error was highlighted in orange (**Fig. 6**). The participants were instructed to keep this error as small as possible at all times. The pursuit task was conducted with their right hand operating the tangible slider's thumb. As in [15], the target followed a pseudo-random path among three paths whose order was randomized between each block. The target moved at constant speed and darted off at pseudo random intervals (between 2 and 4 seconds). The slider's speed was 0.15 × the slider's size (in px per second). The dart-off distance was 0.3 × the slider's size.

With resizable slider (R) only, participants were asked to first reach the target size when the difficulty (i.e. the size of the target) changed, before pursuing the target cursor. Resizing the slider was conducted with both hands operating the bounds of the tangible slider. In **Fig. 6**, this task is presented on the left hand-side of the screen. The target size is green, the user's slider's size is white and the error is red. The aim of this resizing task is to reproduce in a controlled setting the fact that users will adapt the size of their interface to the space available and accordingly degrade their performance in order to keep interacting. As we aim at evaluating the consequence of this resizing on the secondary task, we controlled how participants performed the resizing task as accurately as possible: they could not perform the pursuit task, i.e. their white pursuit cursor was not displayed, as long as they did not reach the target size (±50px). In the case of fixed-size sliders (S and L), the left part of the screen (**Fig. 6**) was empty.

Subjects were asked to be as fast and accurate as possible throughout the experiment for both tasks. Each block started with training, as long as the subject needed. Then, as soon as the subjects pressed a key, the trial started. The task automatically finished after 90 seconds, avoiding the need for any key press validation from the subjects at the end of the trial. Subjects could then take a break and the second trial started after they pressed a key.

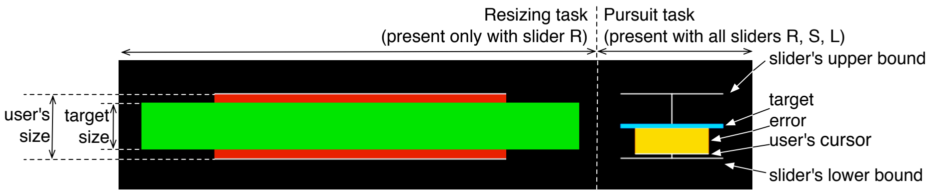

Fig. 6. Close-up screenshot of the experimental tasks during the resizing condition (R). On the left, the primary resizing task: the green rectangle shows the slider's size to reach. The size error is shown in red. On the right, the pursuit task: the thin white slider and the blue moving target to pursue. The pursuit error is shown in orange.

Results. As dependent variables, we considered the *resizing time* (in seconds), the *size* and *size error* (the distance between the size and target size, in cm) and the *pursuit error* (the distance between the cursor and the target, as a percentage of the slider size).

Resizing time. Resizing time was computed from the analysis of the video recording of the experiment. We did not get this information from software logging. Indeed, we wanted to capture the duration between the resizing stimulus and the moment when the user was able to get back to pursuit. For the second, we observed that even though the pursuit task was displayed again on the screen, participants still had to place their hands correctly to be able to pursue again. As a consequence, only video analysis could help us identify the beginning of the pursuit movement.

We found that in average, the participants took 0.7s to resize the slider with our prototype (SD=0.5). We found no impact of the Interval on the resizing time. We also investigated the impact of the resizing distance (2, 4 or 6 cm) and of the direction (skrinking vs. stretching), but found no impact either.

We observed that most participants intertwined both tasks when they could, resizing while continuously keeping their grasp on the thumb to keep pursuing the target. This leads to think that the design of **Fig. 1**(c) is worth studying: it would have been easier if the upper bound of the prototype was fixed on the table, so that they would not need to leave the slider's thumb to use two hands to resize the prototype. We also observed that one participant manipulated the slider as shown in **Fig. 1**(b).

Size and size error. We confirm through this experiment that subjects were able to resize the slider as asked: size error was very close to zero (M=-0.03cm, SD=1.04cm) for the resizable slider. The small and resizable sliders are the only sliders that could adapt to constrained space. They respectively freed more space or just the amount of space that was required. Considering the average size, R was measured 0.57 the size of L (i.e. 3.4cm shorter), whereas S was a fourth of the size of the large slider (i.e. 6cm shorter). R was measured 2.21 the size of S (i.e. 2.42cm larger), whereas L was four times the size of S (i.e. 6cm larger), i.e. almost twice the length of R.

Pursuit error. Considering the pursuit error, we first examined its distribution (**Fig. 7**). As the distribution of the pursuit error is skewed, we considered the median pursuit error as it gives in this case a good measure of location. **Fig. 8** shows the impact of the interval of difficulty change on this median pursuit error.

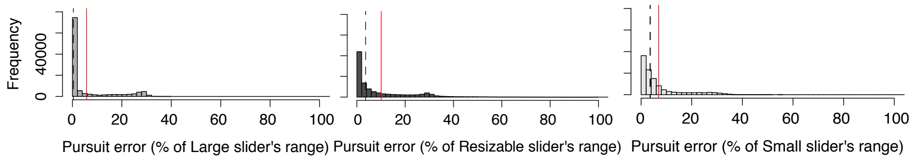

Fig. 7. Distribution of the pursuit error for each device condition (large, resizable and small). Dashed lines show the medians and red lines show the means.

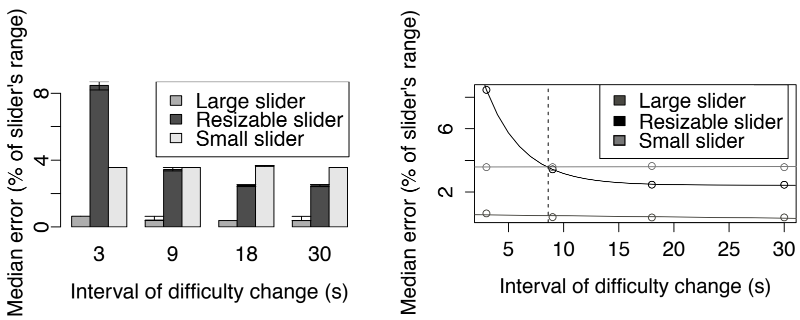

Fig. 8. Left: impact of Slider and Interval of difficulty change on the median error. Right: limit of difficulty change (around 9s) for preferring R over S if space is an issue.

A Levene's test revealed that we could not assume the homogeneity of variances (F(11,332628)=1223.6, p<.001). As a consequence, we performed our analysis through Friedman non-parametric test. We found that Interval has an effect on pursuit error ($\chi 2=1678.887$, $p<.001$) and that Sliders had an effect on pursuit error too ($\chi 2=28337.53$, $p<.001$). In particular, post-hoc tests using Wilcoxon test with Bonferroni correction showed significant differences between all four Intervals ($p<.001$) except between 18 and 30 seconds (**Fig. 8**). It also showed significant difference between all Sliders ($p<.001$). For all Intervals, all Sliders lead to significantly different pursuit error ($p<.001$ for all Intervals/Sliders, except $p=0.008$ between R and S when the difficulty changes every 30 seconds). When the difficulty changes every 3 seconds, the pursuit error with the small slider is 5.53 times the pursuit error with the large slider (i.e. a loss in precision of 2.93% of the slider's range). **The pursuit error with the resizable slider is far more important when the difficulty changes every 3 seconds**: 13.10 times the pursuit error with the large slider (i.e. a loss in precision of 7.82% of the slider's range). **However, while the pursuit error of the small slider does not improve when the difficulty changes less often, the resizable slider gains in precision**: from 2.37 times the pursuit error of the small slider at every 3 seconds (i.e. a loss of precision of 4.89% of the slider's range), the resizable slider becomes more precise than the small slider: its pursuit error is 0.68 times the pursuit error of the small slider at every 18 seconds (i.e. a gain in precision of 1.18% of the slider's range). **To make the best of this result, users with space constraints can keep their slider small at fixed size if the difficulty is changing too often, and start resizing only if the difficulty does not change too often.**

We performed modeling of the medians of the pursuit error for each slider (**Fig. 8**) to find the limit of performance: if the difficulty changes less often than around every 9 seconds and space is an issue, then the resizable slider has to be preferred over the small slider. If space is not an issue, a large slider has to be preferred. If the difficulty changes more often than around every 9 seconds and space is an issue, then it is better to leave the resizable slider at a fixed, small size. This conclusion was confirmed by participants during interviews, as all agreed that 3 seconds was to fast for the resizable slider to be usable whereas 18 and 30 seconds was slow enough for the resizable slider to be usable. For 9 seconds, 3 participants could not decide if it was too fast or slow enough, while 2 found it too fast and 3 found it slow enough.

We can see in **Fig. 7** that the difference between the mean (red) and the median (dashed) is larger in the case of the resizable slider. This is explained by the fact that the mean gives more importance to outliers and to the spread of a skewed distribution. Indeed, in the case of our resizable slider, the error can be higher than with a fixed slider when the user is resizing it. Whereas the error seldomly exceeds 30% of the fixed slider's range (i.e. the target's dart off distance), the error exceeds this threshold in the case of the resizable slider when the user is resizing it. Very high errors occur when the difficulty changes and this increases the mean. As the video analysis showed, the participants sometimes could not control the location of the thumb when they needed two hands to resize the slider. Future improvement of the prototype will investigate ways for the system to control the location of the thumb while resizing the slider (**Fig. 1**(a, c, d)).

As shown in **Fig. 9**, there is an impact on the percentage of time with pursuit error of Intervals ($\chi2$=333.2468, p<.001) and Sliders ($\chi2$=29302.92, p<.001). **Fig. 9** shows that the amount of time with error is very little impacted by the change of difficulty with small ($\chi2$=17.1592, p<.001, effect size V=0.01) and large slider ($\chi2$=64.6802, p<.001, effect size V=0.02)). However, the impact of Intervals is slightly higher in the case of the resizable slider ($\chi2$=890.6538, p<.001, V=0.09). Pursuit errors occurred around 2s more in the 90s trial with the resizable slider than with the small slider when the difficulty changes every 3 seconds ($\chi2$=75.9095, p<.001). **As the resizing occurred less frequently, the pursuit error occurred less often with the resizable slider than with the small slider**: as soon as the difficulty changes every 9 seconds, there is also a significant difference between S and R ($\chi2$= 152.2004, p<.001). When resizing occurs every 9 seconds, users gain 3s of precision with the resizable slider compared to the small slider during the 90s trial and, when resizing occurs every 18s, they gain 6s in a 90s trial). The large slider performs best ($\chi2$= 28919.3, p<.001), at the cost of its larger size.

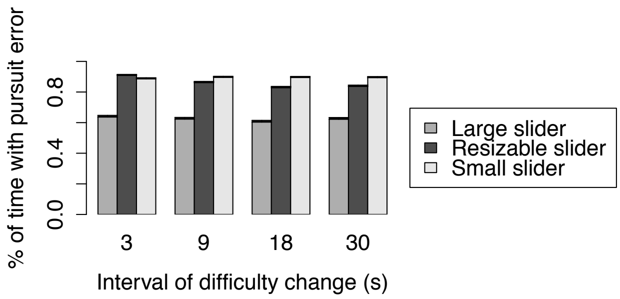

Fig. 9. Impact of Technique and Interval of difficulty change on the percentage of time with pursuit error.

Discussion. Through this experiment, we measured the impact of the additional articulator task for resizing. Overall, participants reported that the manipulation of the prototype was easy. This is confirmed by comparison to previous work: our experiment is not a replication of previous work [15], but the task was identical, and, interestingly, our 8cm slider lead to 6% of mean pursuit error, achieving similar performance as previous 8cm prototype [15]. Depending on the precision demand of the pursuit task, fixed-size or resizable sliders should be considered. If space is not an issue, then a large slider is better as it is more efficient. If space is limited or changing, then designers have to consider two cases:

- If the task demands to be as efficient as possible most of the time, then a resizable slider is better.
- If the task demands not to exceed a threshold of error, then the small slider, kept at fixed size, is better.

For example, for a mobile mixing console allowing to mix a performance from several viewpoint of the venue (e.g., performer, front row, back row, edges, etc.), engineers can face two different requirements: if the show is live, the engineer will prefer to avoid outliers, e.g., uncontrolled high levels. In this case, when the outliers have to be avoided, fixed-sized small sliders would prevent them to occur. On the contrary, if the show is recorded, the engineer would rather control the sliders as precisely as possible for best quality. In this case, when outliers will be cut during editing, a resizable slider is a better option to make the best out of each mixing location.

6 Discussion

We conducted both experiments with the same prototype in order to relate their results. From the second experiment, we found that the time needed to resize was 0.7s (±0.5s). As a consequence, in the worst-case scenario, resizing takes 1.2s. In the first experiment, we measured the mean pointing MT when ID=5(4), at 2.8s(2.1s) for the small slider. The corresponding MT for the large slider is 1.8s(1.5s). If the user has to perform at least two of such pointing tasks consecutively and space is not an issue during these interactions, it is better to first resize the slider. This would allow for a gain of 0.8s(0.1s) in this worst-case scenario - 1.8s(1.1s) in the best-case scenario. When a user, like Helen our illustrator, performs such pointing tasks for parameters adjustments hundreds of times a day, a resizable tangible slider can save a lot of her time over a small tangible slider, and save space over large tangible slider.

The benefits of our prototype for parameters adjustments (pointing and pursuit tasks) are promising. This paper validates the relevance of the concept and shows that further improvements are worth addressing in future work. In particular, several major challenges have to be addressed to improve the design and the prototype:

1. **Improving the pointing performance**: as reported, we felt that very small corrections performed with the thumb of our prototype were slightly more difficult than with a mouse due to static friction. One participant corroborated this hypothesis. In order to bring the pointing performance of our resizable slider to the one of a mouse [7], future improvement of the prototype will investigate ways of decreasing the force needed to start moving the thumb, e.g., decreasing its contact area on the support surface or decreasing its weight.
2. **Decreasing the pursuit error during resizing**: we have two avenues to enable the control of the thumb while resizing. Pausing interaction during resizing is not considered for real-time interaction. First we plan to evaluate a resizable slider with a fixed bound in order for the user to resize with the left hand only and keep controlling the thumb with the right hand (**Fig. 1**c). We can limit the negative impact of this design on the mobility of the slider with an unobtrusive blocking mechanism between the slider's bound and the support surface (e.g., watch, smartphone, tablet, table, etc.). Second, if two hands are used for resizing, two stepper motors could actuate the thumb for the system to maintain its relative position during resizing.
3. **Improving both pointing and pursuit performance through reducing the size of the prototype**: future miniaturization needs to address two issues: slide rail and tracking. Current rigid, retractable tape can be shorten to fit in a smaller volume. Tracking can be done from the support surface [15][28] or magnetic sensors at both ends, computing position and size. In longer term, our vision is addressed by

nanotechnologies, which work towards reconfigurable and controllable material[4] that could be used for implementing such resizable sliders.

7 Conclusion and Future Work

This paper presents a new tangible interaction technique, leveraging shape-change for the users to modify the control properties of a tangible slider: the larger the tangible slider, the more the visual and motor definition for better performance in target selecting and pursuit. Contrastingly, the smaller the tangible slider is, the less the footprint. Users can now balance between performance and size thanks to this resizable slider for zoomable TUIs. We show that the limit of this benefit resides in the frequency of resizing. If the interval between resizing of our proof-of-concept prototype is smaller than around every 9 seconds, the users should better keep the slider at fixed size. This advocates in favor of our interaction technique, as many situations of use do not require a change this frequent, as shown by our application scenarios.

Beyond being readily useful by the community, the outcome of this paper can be improved in follow-up work. The results of our studies pointed to several avenues for improving the design and the prototype. Future work should further study these alternatives to find their impact on users' performance and comfort. Doing so, we would further improve the performance of the resizable slider. Future extensions of this work include exploring if the users actually resize their sliders in an ecological experiment. Second, other tangible widgets, like knobs, could be resized. This raises new questions. For instance, how does the shape of a dial impact users' performance? Which tangible tool is best suited for which task? The presented slider is one concrete implementation of a broader concept that is yet to be investigated, where shape-changing TUIs are tightly coupled with digital information.

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4 see for instance www.cs.cmu.edu/~claytronics/

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